Aerial Surveys in the Stillaguamish and Skagit River Basins
Thermal Infrared and Color Videography

March 16, 2002



Report to:

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Preliminary Report

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Introduction

Thermal infrared remote sensing has been demonstrated as a reliable, cost-effective, and accessible technology for monitoring and evaluating stream temperatures from the scale of watersheds to individual habitats (Karalus et. al., 1996; Torgersen et. al. 1999; Torgersen et. al. 2001). In 2001, the Washington Department of Ecology (WA DOE) contracted with Watershed Sciences, LLC (WS, LLC) to map and assess stream temperatures on selected streams in the Stillaguamish and Skagit River basins using thermal infrared (TIR) remote sensing.

This report presents longitudinal temperature profiles for each survey stream as well as a discussion of the thermal features observed in the basin. TIR and associated color video images are included in the report in order to illustrate significant thermal features. An associated ArcView GIS[1] database includes all of the images collected during the survey and is structured to allow analysis at finer scales. Appendices A and B present a collection of selected TIR and visible band images from the surveys.

Common Methods

Data Collection

Data were collected using a TIR sensor and a visible band color video camera co-located in a gyro-stabilized mount that attached to the underside of a helicopter. The helicopter was flown longitudinally along the stream channel with the sensors in a vertical (or near vertical) position. The surveys were conducted in mid-afternoon in order to capture heat of the day conditions.

The surveys were flown at altitudes that resulted in an image footprint wide enough to view floodplain features while still providing sufficient spatial resolution to measure stream temperatures. The altitudes (and hence image footprints) varied between streams depending on estimated floodplain and stream widths. In some surveys, the altitude was reduced near the headwater reaches in order to account for smaller stream widths. The altitudes used for each survey are specified in the basin overviews later in this report.

TIR images were collected digitally and recorded directly from the sensor to an on-board computer. The TIR detects emitted radiation at wavelengths from 8-12 microns and records the level of emitted radiation in the form of an image. Each image pixel contains a measured value that can be directly converted to a temperature. The raw TIR images represent the full 12 bit dynamic range of the instrument and were tagged with time and position data provided by a Global Positioning System (GPS). The color video camera was aligned to present the same ground area as the TIR sensor.

[1] Geographic Information System

Watershed Sciences distributed in-stream temperature data loggers (Onset Stowaways) in each stream prior to the survey in order to ground truth (i.e. verify the accuracy of) the radiant temperatures measured by the TIR sensor. The advertised accuracy of the Onset Stowaway is ±0.2^{o}C. Meteorological conditions were also recorded during the time of the survey using an automated weather station located at the Arlington, WA Airport.

Data Processing

A computer program was used to create an ArcView GIS point coverage containing the image name, time, and location it was acquired. The coverage provided the basis for assessing the extent of the survey and for integrating the data with other spatially explicit data layers in the GIS. This allowed WS, LLC to identify the images associated with the ground truth locations. The data collection software was used to extract temperature values from these images at the location of the in-stream recorder. The radiant temperatures were then compared to the kinetic temperatures from the in-stream data loggers.

The image points were associated with a river kilometer within the GIS environment. The river kilometers were derived from 1:100K "routed" stream covers from the Environmental Protection Agency (EPA). The route measures provide a spatial context for developing longitudinal temperature profiles of stream temperature. In the laboratory, a computer algorithm was used to convert the raw thermal images (radiance values) to ARC/INFO GRIDS where each GRID cell contained a temperature value. A GIS program was used to display the GRID associated with an image location selected in the point coverage. The GRID was color-coded to visually enhance temperature differences, enabling the user to extract temperature data (Figure 1). The legend on the left of "Grid View" specifies the temperature range associated with each color. The other view window shows the point coverage with the displayed GRID location highlighted in yellow. Each point in the "Stillaguamish FLIR" view represents another image location.

Once in the GRID format, the images were analyzed to derive the minimum, maximum, and median stream temperatures. To derive these measures, a computer program was used to sample the GRID cell (temperature) values in the stream channel. Ten sample points were taken longitudinally in the center of the stream channel. Figure 2 provides an example of how temperatures are sampled. The red "x's" on the psuedo-color TIR image show typical sample locations. Samples were taken to provide complete coverage without sampling the same water twice. Where there were multiple channels, only the main channel (as determined by width and continuity) was sampled. Side channels that had water temperatures different than the main channel were sampled as tributaries. For each sampled image, the sample minimum, maximum, median, and standard deviation was recorded directly to the point coverage attribute file. The median value is the most useful measure of stream temperatures because it minimizes the effect of extreme values.

The temperature of tributaries and other detectable surface inflows were also sampled from images. These inflows were sampled at their mouth using the same techniques described for sampling the main channel. If possible, the surface inflows were identified on the USGS 24K base maps. The inflow name, median temperature, and location (right or left bank looking downstream) were then entered into the point coverage attribute file.

Visible band images corresponding to the TIR images were extracted from the database using a computer-based frame grabber. The images were captured to correspond to the TIR images and provide a complete coverage of the stream. The video images were "linked" to the corresponding thermal image frame in the ArcView GIS environment.

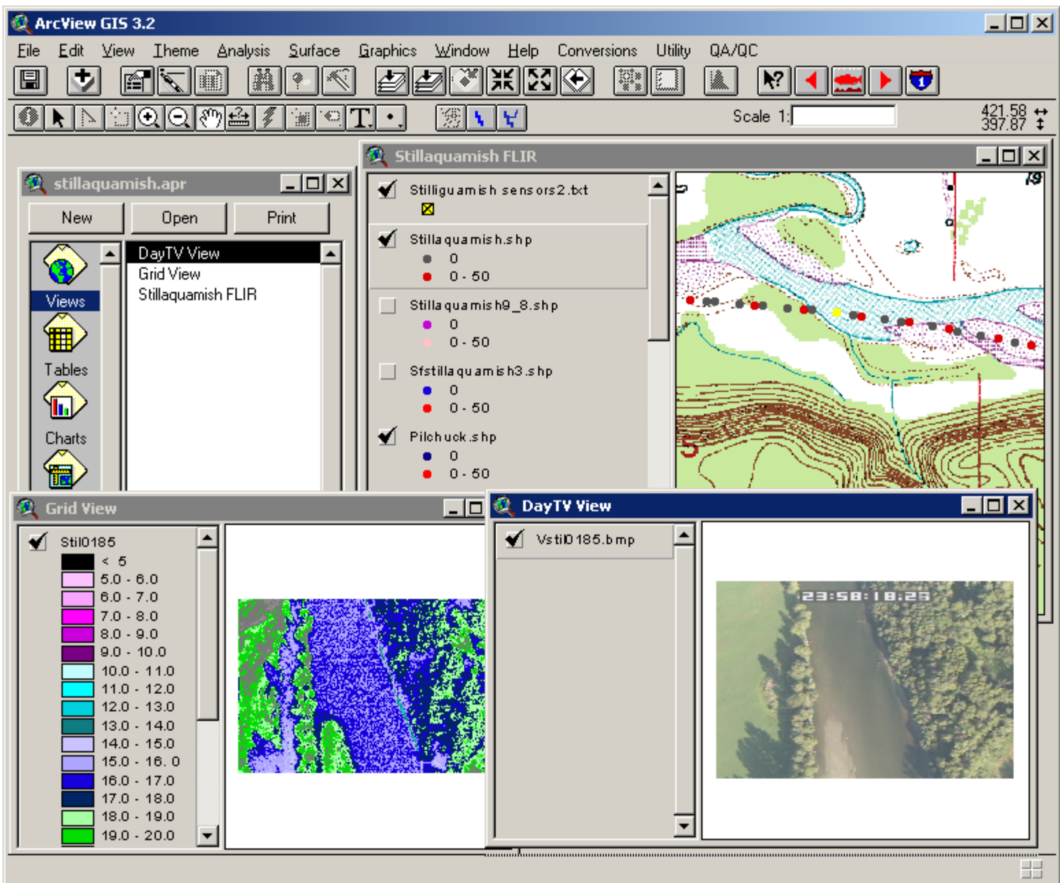
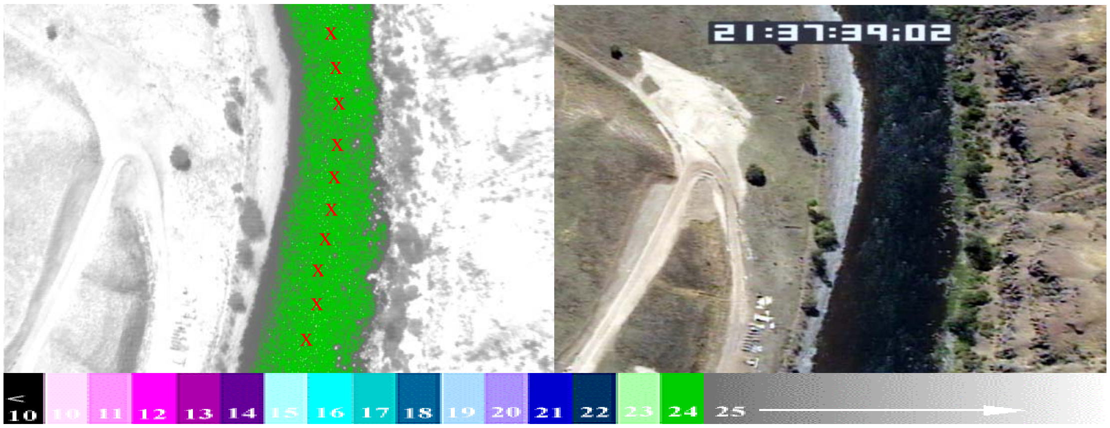


Figure 1 – ArcView display showing a color-coded temperature GRID in one window and the geographic location of the GRID in the other. The orientation of the image is always in the flight direction, which in this case is upstream and opposite the map.



TIR/visible band color images

Figure 2 – Image pair showing typical temperature sampling locations. Temperatures are presented in ^{o}C.

Data Limitations

TIR sensors measure thermal infrared energy emitted at the water's surface. Since water is essentially opaque to thermal infrared wavelengths, the sensor is only measuring water surface temperature. TIR data accurately represents bulk water temperatures in reaches where the water column is thoroughly mixed. However, the imagery may not represent bulk temperatures in reaches where a thermally stratified surface layer has formed.

In addition to vertical mixing, TIR reflections and spatial resolution may also influence the accuracy of the radiant temperatures. The TIR reflections result from changes in background parameters and water surface conditions. Torgersen (2001) documented a difference in the apparent temperatures between pools and riffles, which were related to differences in reflective characteristics at the waters surface. The differences in apparent temperatures between pools and riffles are typically on the magnitude of 0.5^{o}C. Thermal stratification was not considered an issue on any of the streams surveyed in the Stillaguamish and Skagit River basins.

When the stream channel is narrow relative to the pixel size, there are a greater number of hybrid pixels that integrate non-water features such as rocks and vegetation. Consequently, small channel widths can result in higher inaccuracies and more "noise" in the temperature samples. Small channel widths and partial riparian masking were observed on several surveyed streams. The influence of these factors temperature sampling are addressed during the discussion of individual streams.

The ability to detect the stream in the TIR image depends on thermal contrast between the water and surrounding terrain. During the surveys in the Stillaguamish River basin, the apparent temperature of vegetation and other terrestrial features were often similar (i.e. within ±2.0^{o}C) to measured water temperatures. While this does not impact the accuracy of the TIR derived temperatures, the reduced contrast made detection of the stream channel difficult and limited the interpretation of off-channel features. The visible band imagery was used extensively for interpretation of the TIR images.

Stillaguamish River Basin

Overview

Aerial surveys in the Stillaguamish River basin included the Stillaguamish River, Pilchuck Creek, North Fork Stillaguamish River, Deer Creek, South Fork Stillaguamish River, and Canyon Creek (Figure 3). Table 1 summarizes the time and extent of each of the surveys, which were conducted in the mid-afternoon in order to capture heat of the day conditions. The Stillaguamish River was surveyed on both September 7^{th} and 8^{th} for comparison purposes. The surveys were originally scheduled in August, but were postponed until early September due to unfavorable weather in the region during the last two weeks of August.

The Stillaguamish River was surveyed at an average altitude of 2000 ft above ground level (AGL). At this altitude, the image presents a ground width of 215-meters and has a pixel size of 0.4 meters. All other surveys in the basin were conducted at an altitude of 1500 ft AGL. At 1500 ft, the image presents a 160-meter wide footprint with a pixel size of approximately 0.27 meters. All surveys were conducted in an upstream direction and the images are generally oriented in the flight direction.

WS, LLC distributed in-stream temperature data loggers (Onset Stowaways) at 7 locations in the basin prior to the surveys (Figure 3). The in-stream sensors were used to ground truth (i.e. verify the accuracy of) the radiant temperatures measured by the TIR sensor. The advertised accuracy of the Onset Stowaway sensors used by WS, LLC is $\pm 0.2^{o}C$. Meteorological conditions for September 7^{th} and 8^{th} were acquired using a portable weather station located at the Arlington, WA airport (Table 2).

Table 1 - Time, date and distance for the Stillaguamish River surveys.

Stream	Date	Time (PM)	Survey Extent
Deer Cr.	7-Sep	2:00 – 2:38	Mouth to Headwaters
NF Stillaguamish R.	7-Sep	2:50 – 3:58	Mouth to Crevice Cr.
Canyon Cr.	7-Sep	4:02 – 4:42	Mouth to Forks
Stillaguamish R.	7-Sep	4:52 – 5:23	Mouth to Forks
Pilchuck Cr.	8-Sep	1:49 – 2:33	Mouth to Headwaters
Stillaguamish R.	8-Sep	3:03 – 3:24	Mouth to Forks
SF Stillaguamish R.	8-Sep	3:24 – 4:30	Mouth to Coal Cr.

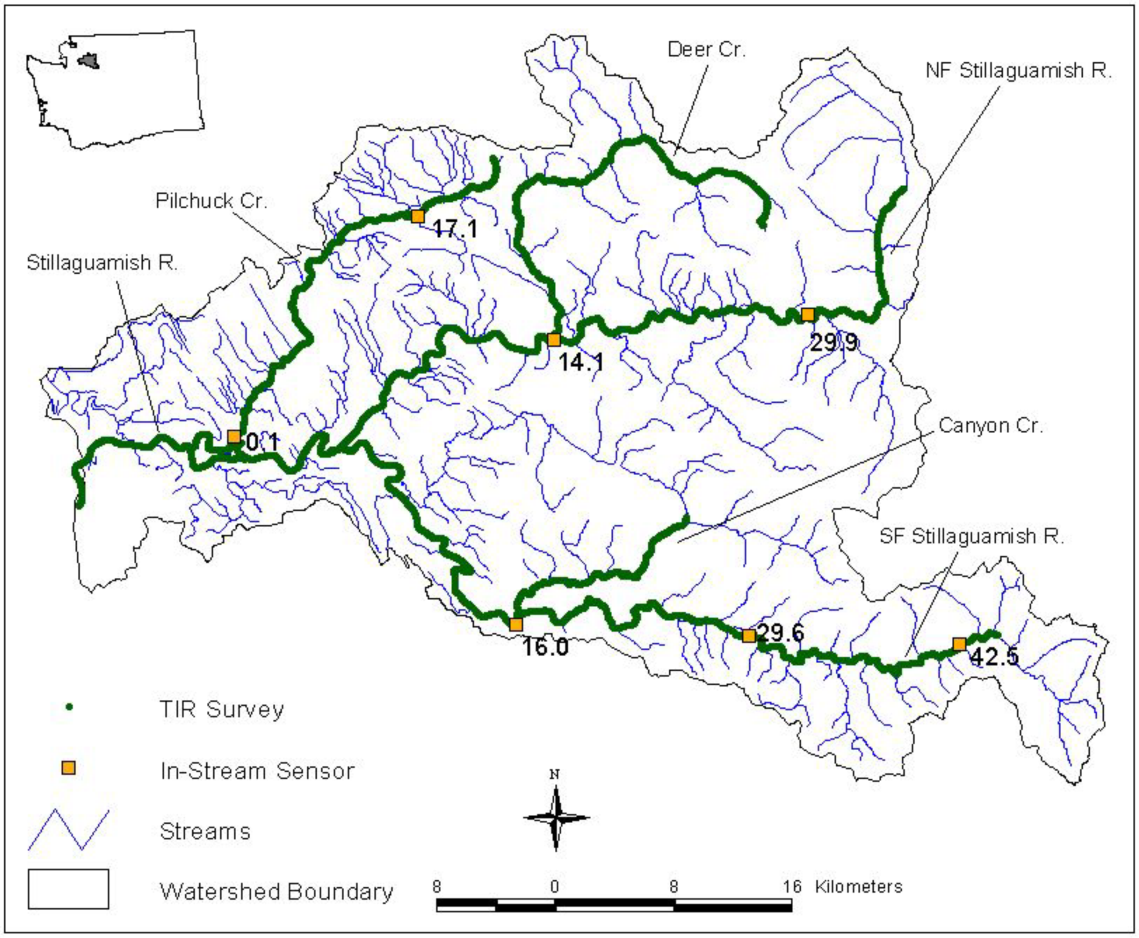


Figure 3 – Map of the Stillaguamish River basin showing streams surveyed using TIR and visible band color video. The map also shows the locations of in-stream sensors used to verify the accuracy of the radiant temperatures.

Table 2 – Meteorological conditions recorded in and around the Stillaguamish River basin for the dates and times of the TIR surveys.

Date	*Time*	*Temp (*C)*	*Temp (*F)*	*RH (%)*
9/7/01	14:00	22.1	71.8	49.7
9/7/01	15:00	19.4	67.0	57.5
9/7/01	16:00	19.8	67.7	59.0
9/7/01	17:00	19.8	67.7	60.1
9/7/01	18:00	18.7	65.6	63.2
9/8/01	13:00	19.8	67.7	63.7
9/8/01	14:00	21.0	69.7	50.7
9/8/01	15:00	22.1	71.8	48.1
9/8/01	16:00	22.1	71.8	50.2
9/8/01	17:00	22.5	72.5	51.8

Results

Thermal Accuracy

Temperatures from the in-stream data loggers were compared to radiant temperatures derived from the imagery for each survey stream (Table 3). The data were assessed at the time the image was acquired, with the radiant values representing the median of ten points sampled from the image at the data logger location. Each surveyed stream was calibrated separately based on the meteorological conditions recorded at the time of the survey. If a consistent difference was observed for all the in-stream sensors, the parameters used to convert radiant values to temperatures were adjusted to provide a better fit to the in-stream sensors. The results showed that radiant temperatures were consistent with in-stream temperatures recorded by data loggers for all streams surveyed. The average difference of 0.3^{o}C observed with Stillaguamish River basin was consistent with TIR surveys conducted in the PNW since 1994 (Torgersen et. al. 2001).

Table 3 – Comparison of ground-truth water temperatures with radiant temperatures derived from the TIR images, September 7 - 8, 2001.

Stream	Image	River Mile	Time PM	In-stream Temp ^{o}C	Radiant Temp ^{o}C	Difference
September 7						
Deer Cr.	deer0026	0.0	2:01	15.2	15.2	0.0
NF Stillaguamish R.	nfst0572	14.0	3:09	15.7	15.4	0.3
NF Stillaguamish R.	nfst1222	29.8	3:33	14.4	14.4	0.0
Canyon Cr.	can0024	0.0	4:03	14.6	14.8	-0.2
Stillaguamish R.	stil0551	9.2	5:13	16.7	16.3	0.4
September 8						
Pilchuck Cr.	pil0027	0.1	1:50	15.6	15.0	.6
Pilchuck Cr.	pil0931	17.1	2:21	12.7	13.2	-0.5
SF Stillaguamish R.	sfs1228	15.9	3:43	14.9	14.9	0.0
SF Stillaguamish R.	sfs2560	42.4	4:29	13.6	13.8	-0.2
Stillaguamish R.	sfs0359	9.1	3:15	15.8	15.5	0.3

Temporal Differences

Figure 4 shows in-stream temperature variation at a single ground truth location on each the North Fork and South Fork Stillaguamish River, as well as the time frame of the TIR remote sensing flights. These surveys were the longest in duration and therefore had the most potential for temperature changes over the course of the flight. At river mile 29.8 of the North Fork, stream temperatures rose from 14.0-14.4°C over the course of the survey. The daily stream temperature maximum (14.4°C) at this location occurred between 3:20 pm and 5:50 pm. In the South Fork, on September 8th, the stream temperature maximum (15.0°C) at river mile 15.9 occurred between 4:10 pm and 4:50 pm. At the two locations examined in Figure 4, water temperature changes over the duration of the flight were negligible.

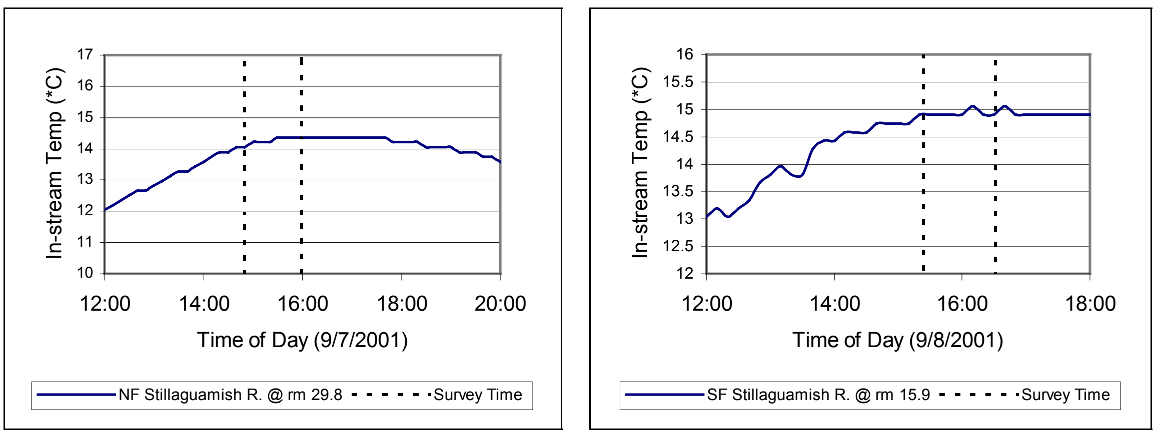


Figure 4 – Stream temperature variation and time of TIR remote sensing over flight for two locations in the Stillaguamish River.

Deer Creek

The median temperatures for each sampled image of Deer Creek were plotted versus the corresponding river mile (Figure 5). The plot also contains the median temperature of all surface water inflows (e.g. tributaries, canals) and off-channel features (side-channels, backwaters). Tributaries are labeled in Figure 5 by river mile with their name and temperature listed in Table 4. Deer Creek was surveyed from its mouth at the North Fork Stillaguamish River to the base of Round Mountain, a total of 22.6 stream miles.

At the upstream end of the survey, water temperatures in Deer Creek were relatively cool at ≈7.2°C. From river mile 22.6, stream temperatures warmed steadily in the downstream direction reaching 14.0°C at river mile 13.7. Stream temperatures dropped by approximately 1.2°C between river miles 12.8 and 12.2. Although no surface water inputs were detected in this segment, an unnamed tributary that originates from the Granite Lake Potholes is shown on the topographic maps entering Deer Creek at river mile 12.8. Examination of the TIR shows significantly cooler bank temperatures through this segment than observed in other mid-reaches of Deer Creek. While the cooler regions were associated with visible shadows, the generally cooler temperatures may suggest wetter soils or different vegetation types than observed in other reaches. Between river mile 12.2 and 1.3, stream temperatures were consistently near 13.0°C with only local thermal variability. Stream temperatures showed a 2.0°C increase between river mile 1.3 and the confluence of the NF Stillaguamish River. A total of 10 surface water inputs were sampled during the analysis. Of the ten, five were sources of thermal cooling to Deer Creek.

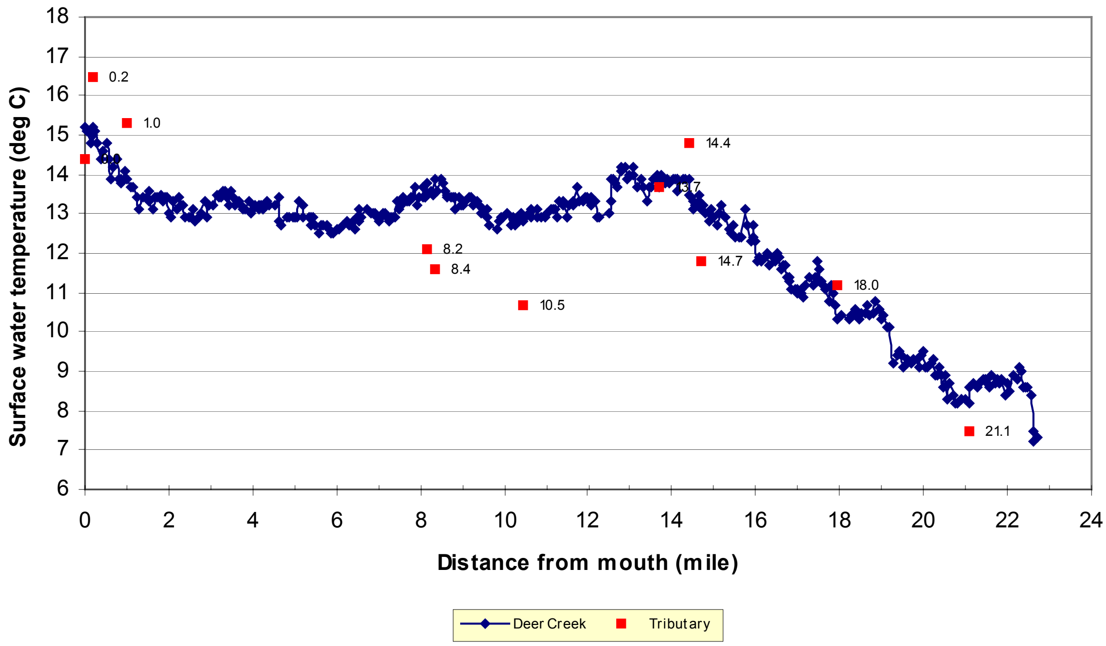


Figure 5 - Median channel temperatures versus river mile for Deer Creek, WA, along with the location of surface water inflows (9/7/01).

Table 4 - Tributary and side channel temperatures for Deer Creek, WA. River miles correspond to data labels shown in Figure 5.

Tributary	Image	km	mile	Tributary Temp °C	Deer Cr. Temp °C	Difference °C
North Fork Stillaguamish R.	deer0030	0.0	0.0	14.4	15.2	-0.8
Side Channel (RB)	deer0042	0.3	0.2	16.5	15.2	1.3
Side Channel (RB)	deer0081	1.6	1.0	15.3	13.9	1.4
Unnamed (RB)	deer0410	13.1	8.2	12.1	13.8	-1.7
Spring (LB)	deer0420	13.4	8.4	11.6	13.9	-2.3
Rick Creek (LB)	deer0517	16.8	10.5	10.7	12.8	-2.1
Little Deer Creek (RB)	deer0664	22.1	13.7	13.7	13.7	0.0
Side Channel (LB)	deer0699	23.2	14.4	14.8	13.9	0.9
Deforest Creek (RB)	deer0718	23.7	14.7	11.8	13.1	-1.3
Higgins Creek (LB)	deer0890	28.9	18.0	11.2	10.3	0.9
Shelf Lake Inlet (LB)	deer1055	34.0	21.1	7.5	8.6	-1.1

North Fork Stillaguamish River

The North Fork Stillaguamish River was flown from the mouth at Stillaguamish River to a location ≈2 miles upstream of Crevice Creek, at total of 40.1 river miles (Figure 6). Tributaries are labeled in Figure 6 by river mile with their name and temperature listed in Table 5.

Water temperatures in the NF Stillaguamish River were ≈13.0°C at the upstream end of the survey. Moving downstream, stream temperatures increased steadily before reaching a local maximum of 14.6°C at river mile 38.5. Stream temperatures decreased by ≈2.0°C between river miles 38.5 and 37.2. Two surface water inputs (South Branch and an unnamed inflow) enter the river in this segment and contribute to the cooling trend. From river mile 37.2, stream temperatures increased steadily reaching a maximum of 16.5°C at river mile 31.7. Squire Creek enters the NF Stillaguamish River at river mile 31.1 and drops mainstem temperatures to ≈13.6°C. Downstream of Squire Creek, water temperatures again increase steadily reaching ≈15.1°C at river mile 27.8. At river mile 27.8, a spring was detected that lowered the mainstem temperatures by ≈2.0°C. This spring (Figure 7) was not documented on the USGS 1:24k scale topographic maps.

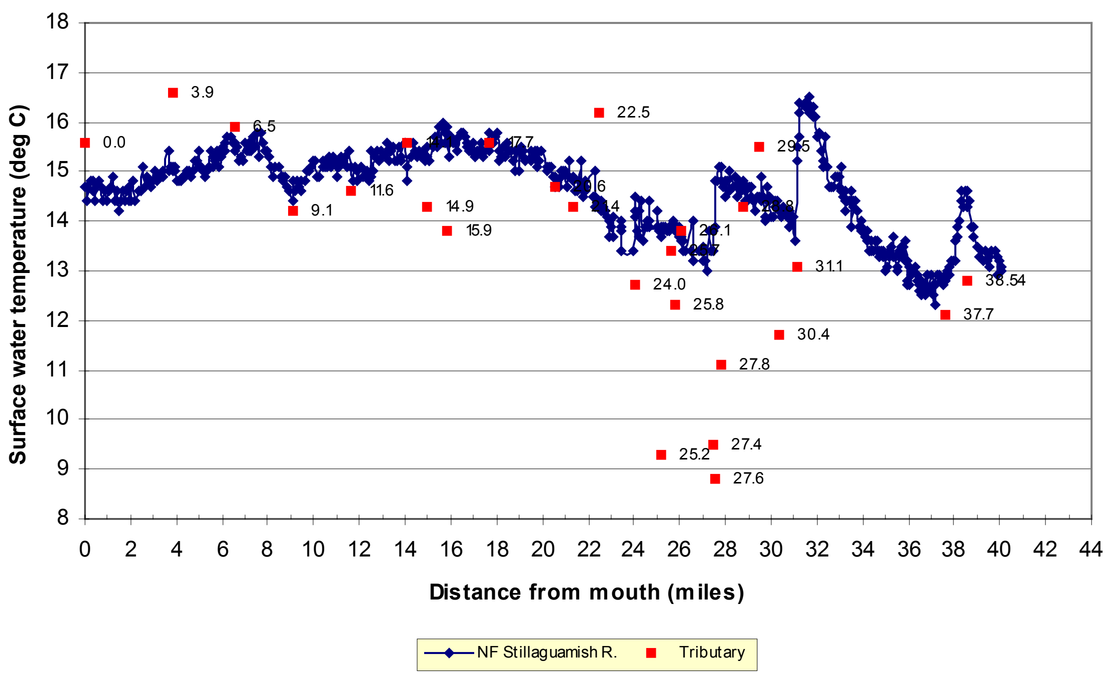


Figure 6 - Median channel temperatures versus river mile for NF Stillaguamish River, WA, along with the location of surface water inflows (9/7/01).

Table 5 - Tributary and side channel temperatures for NF Stillaguamish River, WA. River miles correspond to data labels shown in Figure 6.

Tributary Name	Image	km	mile	Tributary °C	NF Stillaguamish R. Temp °C	Difference Temp °C
South Fork (LB)	nfst0023	0.0	0.0	15.6	14.7	0.9
Rock Creek (RB)	nfst0180	6.3	3.9	16.6	15.0	1.6
Unnamed (RB)	nfst0291	10.5	6.5	15.9	15.6	0.3
Rock Creek (RB)	nfst0390	14.7	9.1	14.2	14.8	-0.6
Side Channel (LB)	nfst0481	18.7	11.6	14.6	15.1	-0.5
Deer Creek (RB)	nfst0575	22.7	14.1	15.6	15.1	0.5
Fry Creek (LB)	nfst0603	24.1	14.9	14.3	15.5	-1.2
Brooks Creek (RB)	nfst0639	25.5	15.9	13.8	15.8	-2.0
Montague Creek (LB)	nfst0717	28.4	17.7	15.6	15.8	-0.2
Rollins Creek (RB)	nfst0830	33.1	20.6	14.7	14.7	0.0
Side Channel (LB)	nfst0865	34.4	21.4	14.3	14.9	-0.6
Side Channel (LB)	nfst0907	36.2	22.5	16.2	14.4	1.8
Boulder River (LB)	nfst0958	38.7	24.0	12.7	14.5	-1.8
Spring (LB)	nfst1007	40.5	25.2	9.3	13.9	-4.6
French Creek (LB)	nfst1025	41.3	25.7	13.4	13.9	-0.5
Unnamed (LB)	nfst1029	41.5	25.8	12.3	13.8	-1.5
Side Channel (RB)	nfst1044	42.0	26.1	13.8	13.7	0.1
Spring (LB)	nfst1114	44.2	27.4	9.5	13.4	-3.9
Spring (LB)	nfst1121	44.4	27.6	8.8	14.8	-6.0
Spring (LB)	nfst1132	44.8	27.8	11.1	15.1	-4.0
Side Channel (LB)	nfst1177	46.4	28.8	14.3	14.7	-0.4
Side Channel (LB)	nfst1204	47.4	29.5	15.5	14.5	1.0
Unnamed, not on map (LB)	nfst1249	48.9	30.4	11.7	14.2	-2.5
Squire Creek (LB)	nfst1286	50.1	31.1	13.1	15.2	-2.1
South Branch (RB)	nfst1600	60.6	37.7	12.1	12.9	-0.8
Unnamed (LB)	nfst1637	62.0	38.5	12.8	14.3	-1.5

From river miles 27.8 to 17.7, stream temperatures increased steadily from ≈13.0°C to ≈15.8°C. Stream temperatures were consistent (≈15.8°C) over the next 4.4 miles (river mile 17.7 to 14.3) showing no significant warming or cooling. This reach roughly extends from the confluence of Montague Creek to just downstream of Deer Creek. From this point, stream temperatures show a slight decrease (1.2°C) reaching a local minimum of 14.4°C at river mile 9.1. Rock Creek also enters the mainstem at river mile 9.1 and is a source of cooling. Stream temperatures increase again between river mile 9.1 and 7.8 reaching 15.6°C. Finally, water temperatures in the NF Stillaguamish River decreased slightly between river mile 7.8 and the mouth at the Stillaguamish River.

Overall, twenty-five surface water inputs were sampled during the analysis. Of the twenty-five, sixteen contributed water that was significantly cooler (i.e. greater than 0.5°C) than the mainstem. Squire Creek (river mile 31.1) and a spring complex (river mile 27.4 – 27.8) directly influenced the shape of the longitudinal temperature profile.

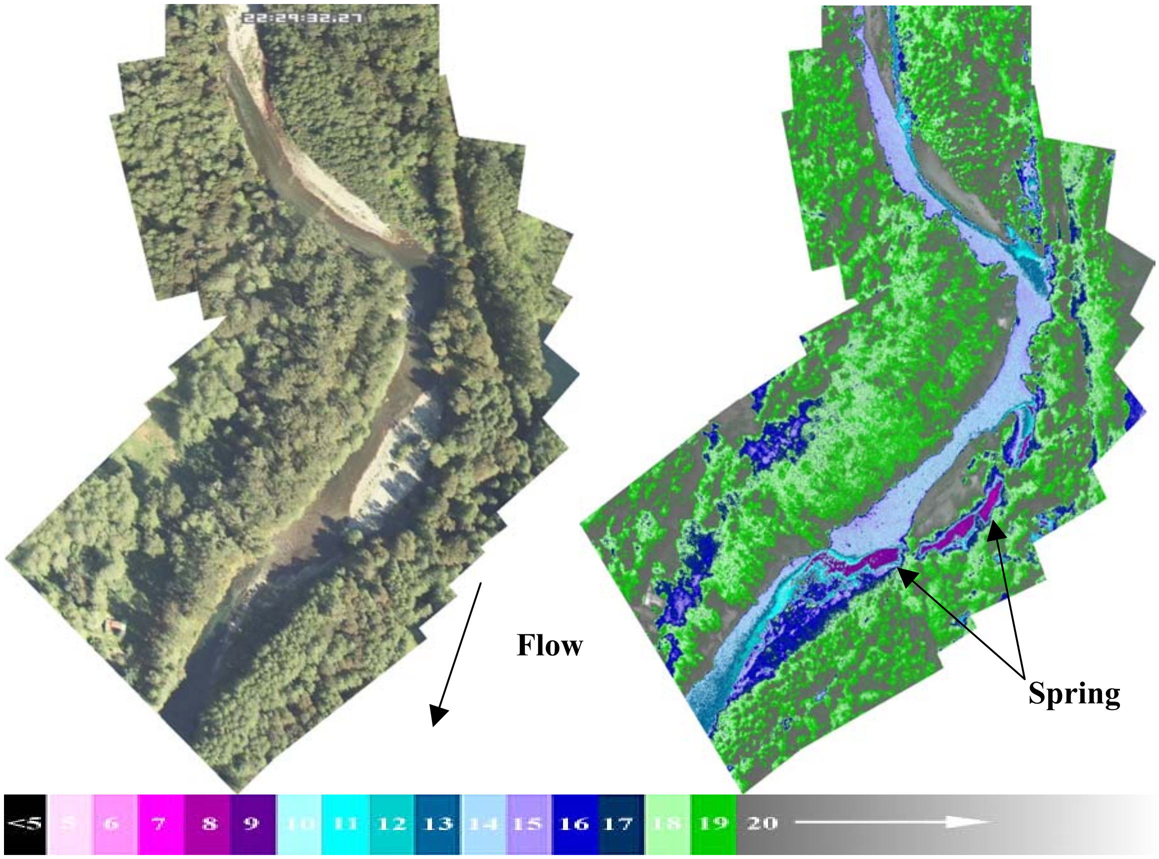


Figure 7 – Visible band/TIR image mosaics (*frames: nfst1118-1132*) showing an apparent spring along the left bank of the NF Stillaguamish River (14.9°C) at river mile 27.8. The inflow lowers the temperatures in the mainstem by ≈2.0°C.

Canyon Creek

The median channel temperature was plotted versus river mile for each sampled image of Canyon Creek (Figure 8). The plot also shows the location of surface water inputs (i.e. tributaries, seeps, etc.) that were detected during the analysis. The temperature and location of the surface water inputs are summarized in Table 6. Canyon Creek was surveyed from the South Fork Stillaguamish River upstream to the North Fork and South Fork confluence, a total of 11.2 miles.

Canyon Creek shows an overall warming trend in the downstream direction with some local spatial variability. At the time of the survey, the North Fork had water temperatures that were ≈1.4°C cooler than those observed in the South Fork. A small (≈1.0°C), but notable temperature drop was observed in the profile at river mile 8.5. This temperature decrease was not associated with any surface water inflows. From river mile 8.5 to the mouth, stream temperatures continued to increase steadily reaching a maximum of 15.4°C at river mile 0.5. A slight temperature decrease was observed in the lower ½ mile of Canyon Creek. Water temperatures in Canyon Creek were ≈0.7°C cooler than those measured in the SF Stillaguamish River at the confluence.

Excluding the North and South Forks, four surface water inputs were sampled and all contributed water that was cooler than the mainstem. Two apparent springs (*Appendix A image frames can0457 and can0627*) were detected during the survey at river mile 7.6 and 11.0. However, shadows in the visible band images made it difficult to positively identify surface water in these areas and some uncertainty exists in the spring classification.

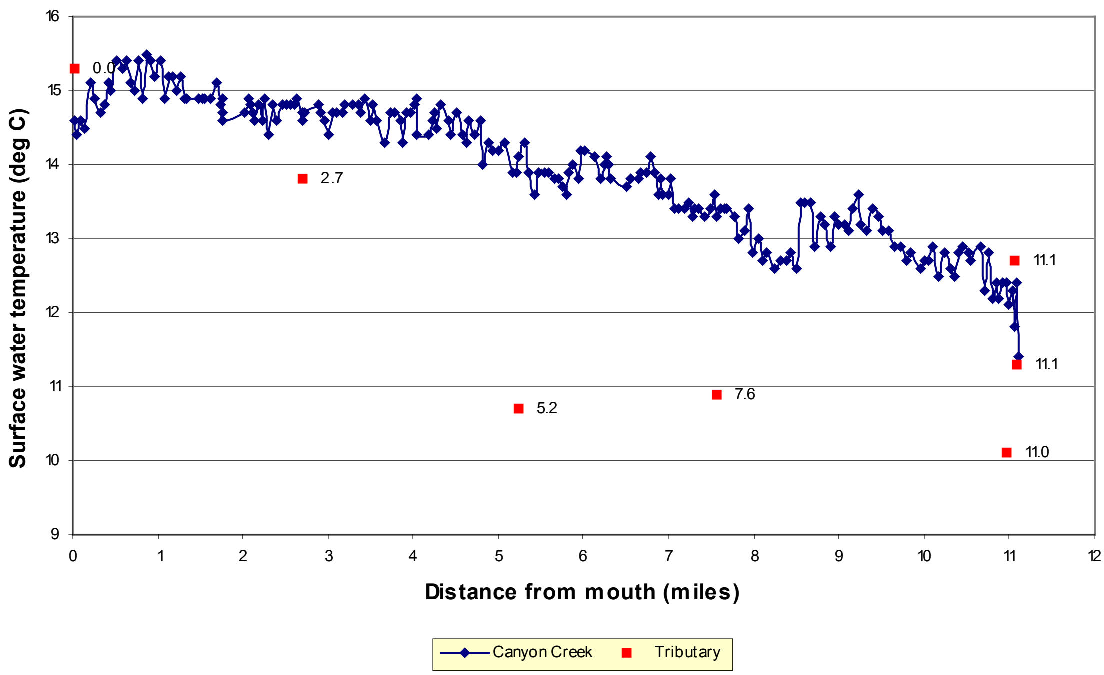


Figure 8 - Median channel temperatures versus river mile for Canyon Creek, WA, along with the location of surface water inflows (9/7/01).

Table 6 - Tributary and other surface water input temperatures for Canyon Creek, WA. River miles correspond to data labels shown in Figure 8.

Tributary Name	Image	km	mile	Tributary Temp °C	Canyon Cr. Temp °C	Difference Temp °C
SF Stillaguamish River (LB)	can0029	0.0	0.0	15.3	14.6	0.7
Jordan Ponds Inlet (RB)	can0182	4.4	2.7	13.8	14.7	-0.9
Mud Lake Inlet (RB)	can0319	8.4	5.2	10.7	14.1	-3.4
Cool Seep (LB)	can0457	12.2	7.6	10.9	13.3	-2.4
Spring (LB)	can0627	17.6	11.0	10.1	12.4	-2.3
South Fork (LB)	can0635	17.8	11.1	12.7	11.8	0.9
North Fork (RB)	can0636	17.8	11.1	11.3	12.4	-1.1

Stillaguamish River

The Stillaguamish River was surveyed from its mouth to the confluence of the North and South forks, a distance of approximately 18 miles. The Stillaguamish River was surveyed on September 7th between 4:52 and 5:23 PM. The median temperature from each sampled image was plotted versus river mile (Figure 9). The plot also shows the location and temperature of all surface water inputs (i.e. tributaries and side channels) detected during the survey. Table 7 summarizes the temperature of each sampled surface water inputs. Since this flight was conducted late in the day, the Stillaguamish River was flown again on September 8th between 3:02 and 3:23 PM for comparison purposes. Figure 10 shows the temperature profiles derived from both surveys.

At the time of the September 7th survey, water temperatures in the North Fork Stillaguamish River were ≈1.0°C cooler than the South Fork. The Stillaguamish River had water temperatures of ≈16.8°C downstream of the confluence and a slight, but notable temperature decrease (-1.2°C) was observed between the confluence and river mile 10.3. An apparent cool water seep (Figure 11) was detected at river mile 15.7. Although it was the only input detected through this reach, it suggests that sub-surface exchanges within the stream channel are a possible cooling mechanism through this reach. Downstream of river mile 10.3, water temperatures increased slightly before remaining consistently around 16.0°C (±0.5°C) between river mile 8.0 and the mouth.

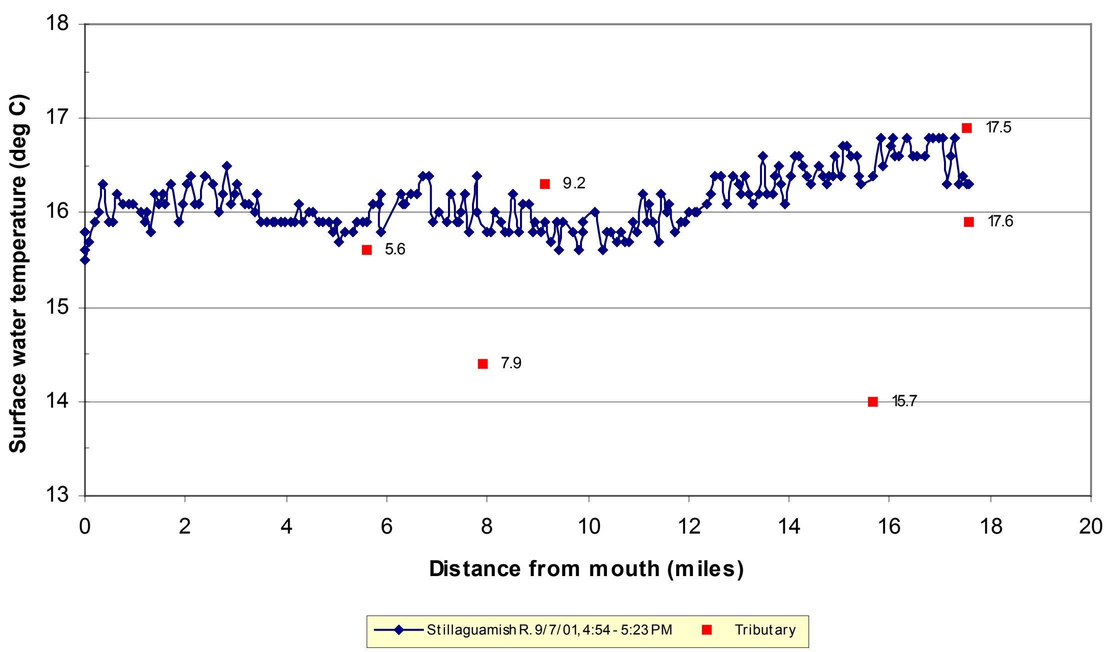


Figure 9 - Median channel temperatures versus river mile for Stillaguamish River, WA, along with the location of surface water inflows (9/7/01).

Table 7 - Tributary temperatures for the Stillaguamish River, WA (9/7/01). River miles correspond to data labels shown in Figure 9.

Tributary	Image	km	mile	Tributary Temp °C	Stillaguamish R. Temp °C	Difference Temp °C
Portage Creek (LB)	stil0346	12.7	7.9	14.4	15.8	-1.4
South Slough (LB)	stil0412	9.0	5.6	15.6	15.9	-0.3
Pilchuck Cr (RB)	stil0551	14.7	9.2	16.3	15.9	0.4
Cool Seep (RB)	stil0797	25.2	15.7	14.0	16.4	-2.4
South Fork (LB)	stil0862	28.2	17.5	16.9	16.3	0.6
North Fork (RB)	stil0863	28.3	17.6	15.9	16.3	-0.4

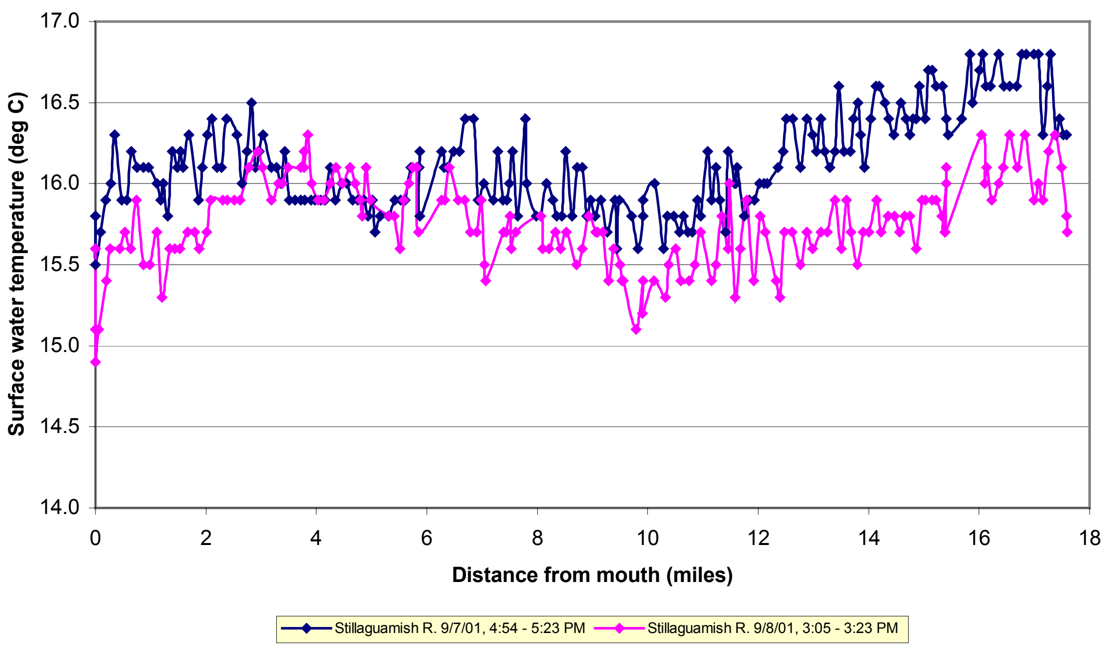


Figure 10 – Comparison of the median channel temperatures versus river mile for surveys flown on consecutive days on the Stillaguamish River, WA.

The longitudinal temperature patterns were consistent between the two surveys of the Stillaguamish River (Figure 10). Temperatures were generally cooler for the September 8th flight, which was conducted earlier in the day. However, both profiles show the same cooling trend downstream of the NF and SF confluence with minimum temperatures observed near river mile 10.0. Stream temperature patterns were consistent between river mile 10.0 and river mile 2.0. When comparing the profiles recall that the temperature profiles derived from TIR images characteristically show noise of ±0.4°C due to changes in ambient reflections and atmospheric conditions (*see data limitations*).

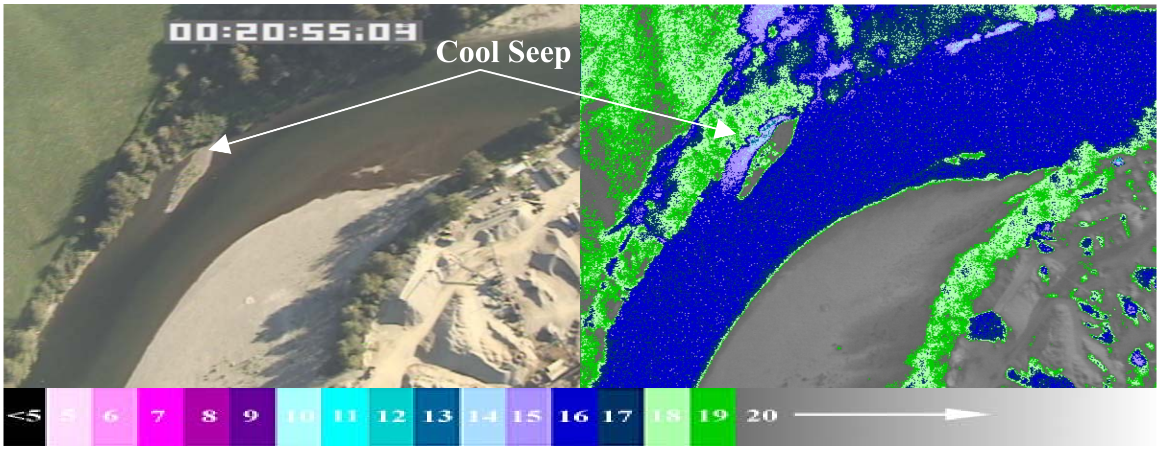


Figure 11 – Visible band/TIR image showing the Stillaguamish River (16.4°C) at river mile 15.7. Flow direction is from the top right to bottom left of the image. An apparent cool water seep (14.0°C) was detected along the right bank.

Pilchuck Creek

Pilchuck Creek was surveyed upstream from the mouth to headwaters, a distance of 20.5 miles. The median channel temperatures for each sampled image of Pilchuck Creek were plotted versus river mile (Figure 12). The plot also shows the location of tributaries and other surface water inflows detected during the survey. Table 8 summarizes the temperature of each surface input sampled during the analysis. Only surface water inflows that were visible in the imagery were sampled. Other tributary inflows may have been masked by riparian vegetation.

Water temperatures in Pilchuck Creek showed a general warming trend from headwaters to the mouth, but exhibited a high degree of spatial thermal variability at the reach scale. Six surface water inputs were sampled during the analysis. Of the six, two side channels had temperatures that were significantly different (i.e. ± 0.5°C) than the mainstem of Pilchuck Creek. These results suggest that the spatial variability observed in the profile was not in response to surface water inputs.

At the upstream end of the survey at river mile 21.7, stream temperatures were ≈12.0°C. From river mile 21.7, stream temperatures increased rapidly in the downstream direction reaching a local maximum of 15.2°C at river mile 19.7. The stream was narrow and often masked by riparian vegetation through this reach and temperature samples were taken where the stream surface was visible in the imagery. Consequently, temperature samples were taken less frequently in the upstream end of the survey. Narrow stream channels also result in more hybrid pixel and therefore more noise in the profile (*see data limitations*). Stream temperatures decreased from 15.2°C to 13.6°C between river miles 19.7 and 19.1 and continued to decrease to ≈13.0°C at river mile 18.2. The source of cooling through this reach was not apparent from the thermal imagery. Stream temperatures remained near 13.1°C (±0.3°C) over the next 1.7 miles to river mile 16.5. From river mile 16.5, stream temperatures increased by ≈1.4°C reaching 14.4°C at river mile 16.0. Bear Creek joins Pilchuck Creek through this reach, but did not contribute temperatures that were significantly different than the mainstem. Water temperatures in Pilchuck Creek decreased by 2.0°C between river miles 15.7 and 14.5. There were no surface water inflows detected through this reach. Between river miles 14.5 and 11.3, stream temperatures increased from ≈12.4°C to ≈15.1°C, although local spatial variability was noted through this reach. Stream temperatures again decreased to ≈13.2°C at river mile 10.5. As with other cooling reaches, no surface water inflows were detected that would account for the observed cooling trend. Water temperatures increased steadily between river miles 10.5 and 8.1 reaching a local maximum of 15.5°C at river mile 8.0. Stream temperatures dipped again to ≈14.0°C at river mile 7.0, but generally increased from river mile 7.0 to the confluence with the Stillaguamish River.

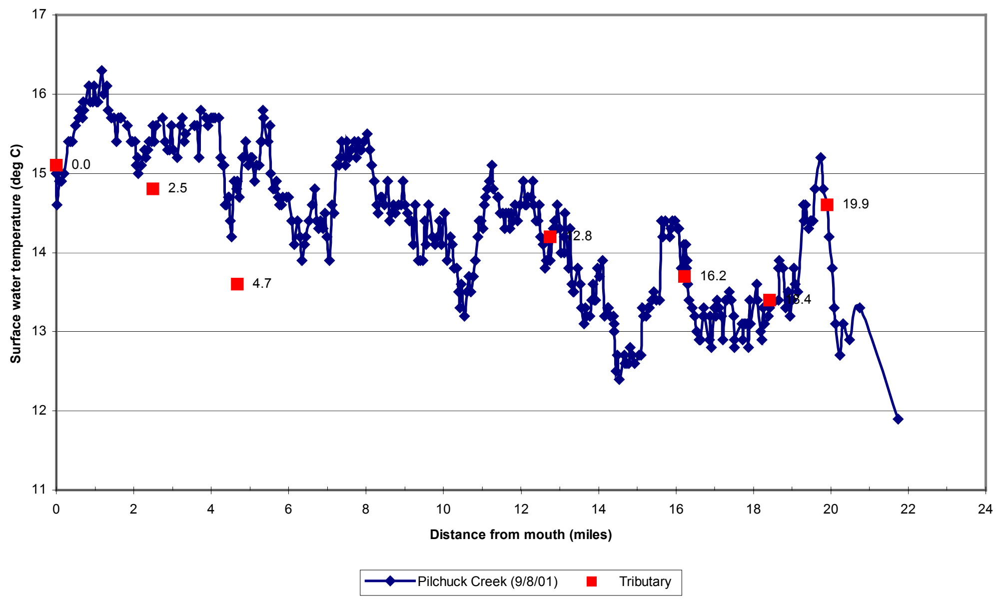


Figure 12 - Median channel temperatures versus river mile for Pilchuck Creek, WA along with the location of surface water inflows (9/8/01).

Table 8 - Tributary temperatures for Pilchuck Creek, WA (9/8/01). River miles correspond to data labels shown in Figure 12.

Tributary Name	Image	km	mile	Tributary Temp °C	Pilchuck Cr. Temp °C	Difference Temp °C
Stillaguamish (LB)	pil0019	0.0	0.0	15.1	15.0	0.1
Side Channel (LB)	pil0145	4.0	2.5	14.8	15.6	-0.8
Side Channel (LB)	pil0276	7.5	4.7	13.6	14.9	-1.3
Crane Creek (LB)	pil0684	20.5	12.8	14.2	13.9	0.3
Bear Creek (RB)	pil0858	26.1	16.2	13.7	13.8	-0.1
Unnamed (RB)	pil0999	29.7	18.4	13.4	13.3	0.1
Unnamed (RB)	pil1082	32.0	19.9	14.6	14.6	0.0

South Fork Stillaguamish River

The South Fork (SF) Stillaguamish River was surveyed upstream from its mouth to the confluence of Coal Creek, a distance of approximately 44.4 miles. The median temperatures for each sampled image of the SF Stillaguamish was plotted versus the corresponding river mile (Figure 13). The plot also contains the location and temperature of all surface water inflows (i.e. tributaries, canals) and off channel features (side channels, backwaters, etc.) detected during the analysis. Tributaries are labeled in Figure 13 by river mile with their name and temperature listed in Table 9. Only the surface water inflows that could be positively identified in the imagery were included. In some cases, tributaries and other surface water inputs were obscured by riparian vegetation.

Between river miles 44.4 and 18.0, water temperatures in the SF Stillaguamish River ranged from 12.6°C to 15.7°C with variation occurring at the reach scale. At the upstream end of the survey (river mile 44.4), stream temperatures were ≈12.6°C and warmed slightly in the downstream direction reaching ≈14.0°C at river mile 42.2. Between river miles 42.2 and 40.0, the river showed a slight cooling trend returning to ≈12.6°C at river mile 40.0. Marten Creek (river mile 44.4) was observed as a source of cooling within this reach. Moving downstream, the stream warmed at a consistent rate reaching ≈15.1°C at river mile 33.8. Stream temperatures dropped slightly (≈1.0°C) between river miles 33.8 and 31.5 with two tributaries (Wiley Creek and Wisconsin Creek) contributing cooler water in this reach. Between river miles 31.5 and 30.0, stream temperatures increased by ≈1.3°C before remaining consistently about 15.2°C (±0.6°C) over the next 7.5 miles to river mile 22.5.
The consistent temperatures between river miles 30.0 and 22.5 corresponds to the area labeled as the Robe Valley on the topographic maps. The consistent water temperatures through this reach suggest possible buffering processes such as subsurface exchanges through the channel substrate. Four surface inflows were sampled between river mile 31.5 and river mile 22.5 and each were sources of thermal cooing. Stream temperatures showed a decrease of ≈2.0°C between river miles 22.5 and 20.8. No surface water inflows were detected at this location. Examination of the topographic map shows that river mile 22.5 roughly corresponds to the beginning of a canyon reach downstream of the Robe Valley. Stream temperatures remain at approximately 13.4°C between river miles 20.8 and 18.0.

Downstream of river mile 18.0, temperatures in the SF Stillaguamish River increased steadily reaching approximately 16.0°C at river mile 12.7. Between river mile 12.7 and the confluence of the NF Stillaguamish River, stream temperatures were variable ranging between 15.5°C and 16.7°C. Overall, fifteen surface water inputs were sampled on the SF Stillaguamish River. Of the fifteen, eleven contributed water that was significantly cooler (i.e. greater than 0.5°C) than the mainstem. Two side channels contributed water that was significantly warmer than the mainstem. Canyon Creek, a major tributary, contributed water that was essentially the same temperature at the SF Stillaguamish.

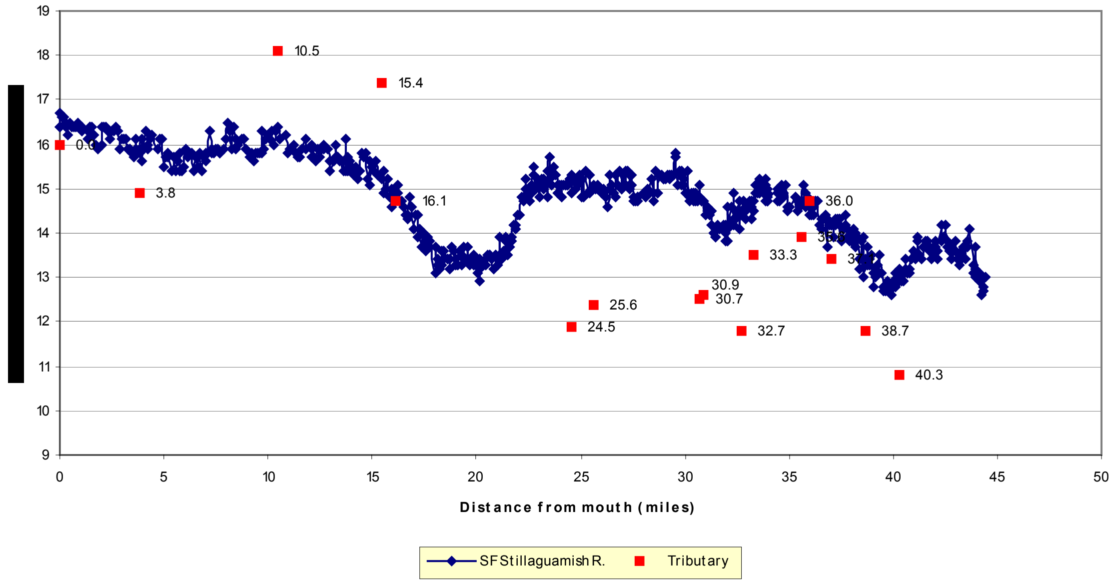


Figure 13 - Median channel temperatures versus river mile for SF Stillaguamish River, WA, along with the location of surface water inflows (9/8/01).

Table 9 - Tributary temperatures for the SF Stillaguamish River, WA. River miles correspond to data labels shown in Figure 13.

Tributary Name	Image	km	mile	Tributary Temp °C	SF Stillaguamish R. Temp °C	Difference
North Fork (RB)	sfs0637	0.0	0.0	16.0	16.4	-0.4
Jim Creek (RB)	sfs0786	6.1	3.8	14.9	15.8	-0.9
Side Channel (LB)	sfs1025	16.8	10.5	18.1	16.4	1.7
Side Channel (RB)	sfs1206	24.8	15.4	17.4	15.2	2.2
Canyon Creek (RB)	sfs1234	25.9	16.1	14.7	14.9	-0.2
Unnamed (RB)	sfs1640	39.5	24.5	11.9	15.3	-3.4
Side Channel (LB)	sfs1692	41.3	25.6	12.4	15.1	-2.7
Twentytwo Creek (LB)	sfs1942	49.4	30.7	12.5	15.1	-2.6
Hemple Creek (LB)	sfs1955	49.7	30.9	12.6	14.7	-2.1
Wisconson Cr. (LB)	sfs2039	52.6	32.7	11.8	14.5	-2.7
Wiley Creek (RB)	sfs2072	53.6	33.3	13.5	14.5	-1.0
Boardman Creek (LB)	sfs2182	57.2	35.6	13.9	14.7	-0.8
Gordon Creek (RB)	sfs2202	57.9	36.0	14.7	14.6	0.1
Mallardy Creek (LB)	sfs2265	59.7	37.1	13.4	14.2	-0.8
Blackjack Creek (LB)	sfs2355	62.2	38.7	11.8	13.4	-1.6
Marten Creek (RB)	sfs2451	64.9	40.3	10.8	13.1	-2.3

Discussion

TIR remote sensing was used to map stream temperatures for the Stillaguamish River, WA and major tributaries in the basin. The surveys were conducted in the mid-afternoon on September 7th and 8th in order to capture maximum daily stream temperatures. The flights were delayed until September due to unfavorable weather in the last two weeks of August. In particular, a large rain event on August 20th resulted in increased volume flows than observed earlier in the summer. However, data collected on other streams in the PNW over the past four years have shown that while the absolute stream temperatures change, the spatial patterns of warming and cooling remain consistent. The overall effect of the delay was generally cooler water and terrestrial environment.

Spatial temperature patterns were different for each of the streams surveyed in the basin. In some cases, point source inflows such as tributaries accounted for observed variability in the profile. For example, the survey of the NF Stillaguamish River detected an apparent spring input that lowered stream temperatures by 2.0°C. In other reaches, the mechanisms driving the spatial temperature variability were not apparent from the imagery.
Pilchuck Creek exhibited several cooling reaches that were not associated with surface water inputs or any obvious topographic factors. Follow-on analysis should include examining these spatial temperature patterns in relation to other spatial factors (such as topography, channel morphology, land-use, etc.) that influence stream heating and cooling.

Appendix A contains example visible band and thermal infrared images for surveys conducted in the Stillaguamish River basin. The TIR images were color mapped to highlight the range of water temperatures found in the stream. In some cases (*see data limitations*), low thermal contrast existed between the stream and bank-side vegetation. The low contrast made it more difficult to see the stream and distinguish off channel features, but did not generally impact the ability to obtain accurate temperature samples. Color mapping of the images often exaggerates the impact of low thermal contrast within the image scene. The raw TIR images (in GRID format) provided with the database allow remapping the TIR images to highlight specific features in reaches where thermal contrast is low.

The TIR surveys lay a basic groundwork to integrate the WA Total Maximum Daily Load (TMDL) process into watershed planning and restoration. In particular, water temperature modeling can provide a powerful tool to address the biophysical parameters that are driving stream temperature patterns and suggest multiple pathways for remediation. In addition, the longitudinal temperature patterns provide a robust template to construct a monitoring program, in particular the deployment of in-stream temperature sensors.

Skagit River Basin

Overview

Aerial surveys were conducted on Carpenter Creek and Nookachamps Creek in the Skagit River Basin (Figure 14) on August 31, 2001. The streams were surveyed upstream from mouth to headwater. The surveys were conducted an average altitude of 1200 ft AGL. At this altitude, the image presents a ground area of approximately 130 meters wide and a pixel size of ≈0.2 meters.

WS, LLC distributed two in-stream temperature data loggers (Onset Stowaways) in Nookachamps Creek prior to the survey. The in-stream sensors were used to ground truth (i.e. verify the accuracy of) the radiant temperatures measured by the TIR sensor. Unfortunately one of these sensors was lost. A data logger located in the mouth of Pilchuck Creek in the Stillaguamish River basin provided an addition ground truth point for the surveys. Meteorological conditions for the time frame of the surveys on August 31 were acquired using a portable weather station located at the Arlington, WA airport (Table 10). Air temperatures were between 21.0°C and 23.2°C during the course of the survey. Weather conditions were sunny and clear on the morning of August 31, but clouds and cooler air temperatures moved in by late afternoon.

Table 10 - Meteorological conditions recorded in and around the Skagit River basin for the dates and times of the TIR surveys.

Time	*Temp (°C)*	*RH (%)*
15:00	23.2	49.7
16:00	21.0	55.9
17:00	21.0	59.0

Results

Thermal Accuracy

Temperatures from the in-stream data loggers were compared to radiant temperatures derived from the imagery for each survey stream (Table 11). The data were assessed at the time the image was acquired, with the radiant values representing the median of ten points sampled from the image at the data logger location. The data logger located at river mile 1.9 on Nookachamps Creek was lost. As a result, two sensors (one in the Stillaguamish Basin) were used to ground truth the TIR images and both were within 0.4°C of the radiant temperatures derived from the TIR images.

Table 11 – Comparison of ground-truth water temperatures with radiant temperatures derived from the TIR images for August 31, 2001.

Stream	Image	River Mile	Time PM	In-stream Temp °C	Radiant Temp °C	Difference
August 31						
Nookachamps Cr.	Nook0753	12.6	3:49	14.9	15.3	-0.4
Pilchuck Cr.	Pil0017	0.1	4:07	18.3	18.5	-0.2

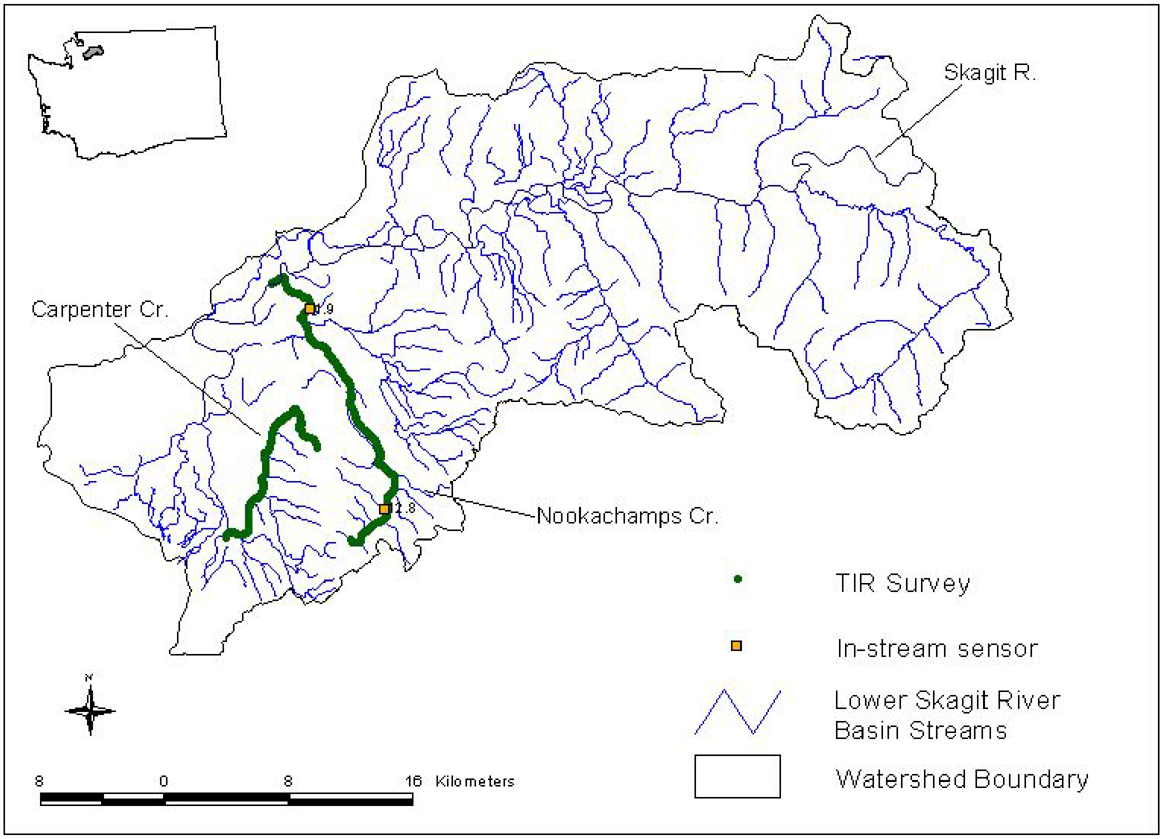


Figure 14– Map of the Skagit River basin showing streams surveyed using TIR and visible band color video. The map also shows the locations of in-stream sensors used to verify the accuracy of the radiant temperatures.

Longitudinal Profiles

Carpenter Creek

Carpenter Creek was surveyed from the Steamboat Slough upstream to the headwaters, a distance of 9.1 miles. The median temperatures for each sampled image of Carpenter Creek were plotted versus the corresponding river mile (Figure 15). Two surface water inputs were detected during the survey and both are labeled on the profile. At the upstream end of the survey, Carpenter Creek was small and difficult to detect through the riparian vegetation. As a consequence, the images were sampled intermittently at locations where the stream could be distinguished. The difficulty detecting the stream persisted from the headwaters downstream to river mile 4.9. At river mile 4.7, Carpenter Creek becomes a canal for the remainder of its length. The canal (Carpenter Creek) showed signs of thermal stratification between miles 4.6 and 2.8. Through this reach, the canal surface temperatures approached measured air temperatures. At river mile 2.8 there is very little visible surface flow. Surface water reappears at river mile 2.6, but is intermittent over much of the lower 2.5 miles of the stream. Figure 16 provides a point pattern map of the Carpenter Creek Survey and illustrates the canal portion of the stream and where temperature sampling becomes intermittent in the headwater reaches.

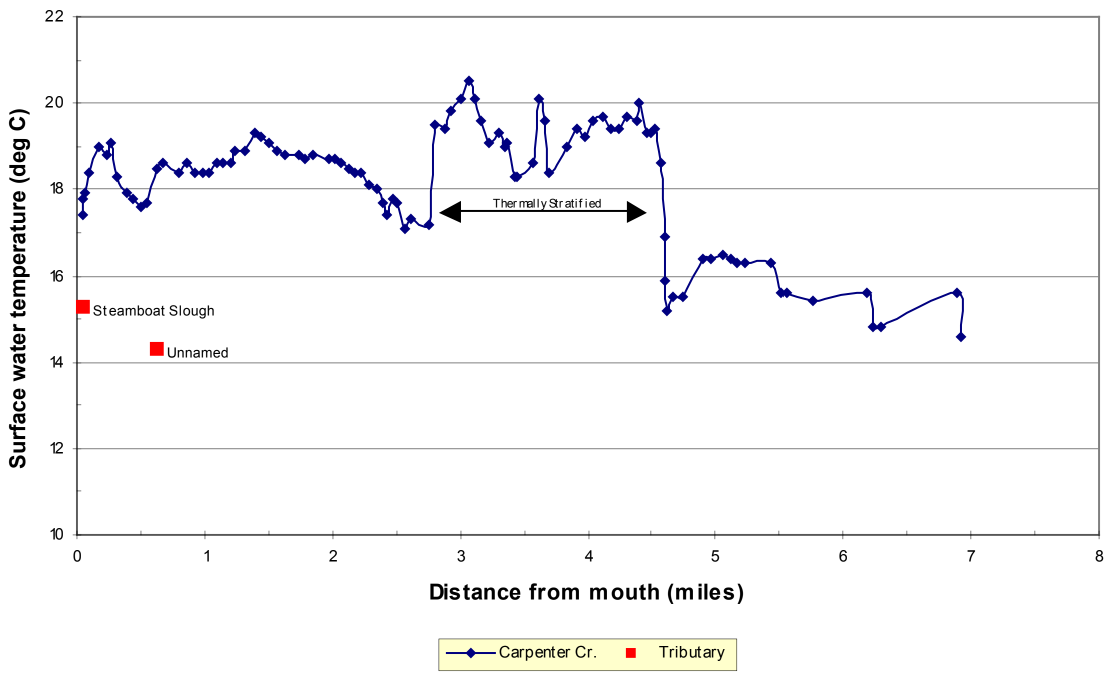


Figure 15 – Median channel temperatures versus river mile for Carpenter Creek, WA (8/31/01).

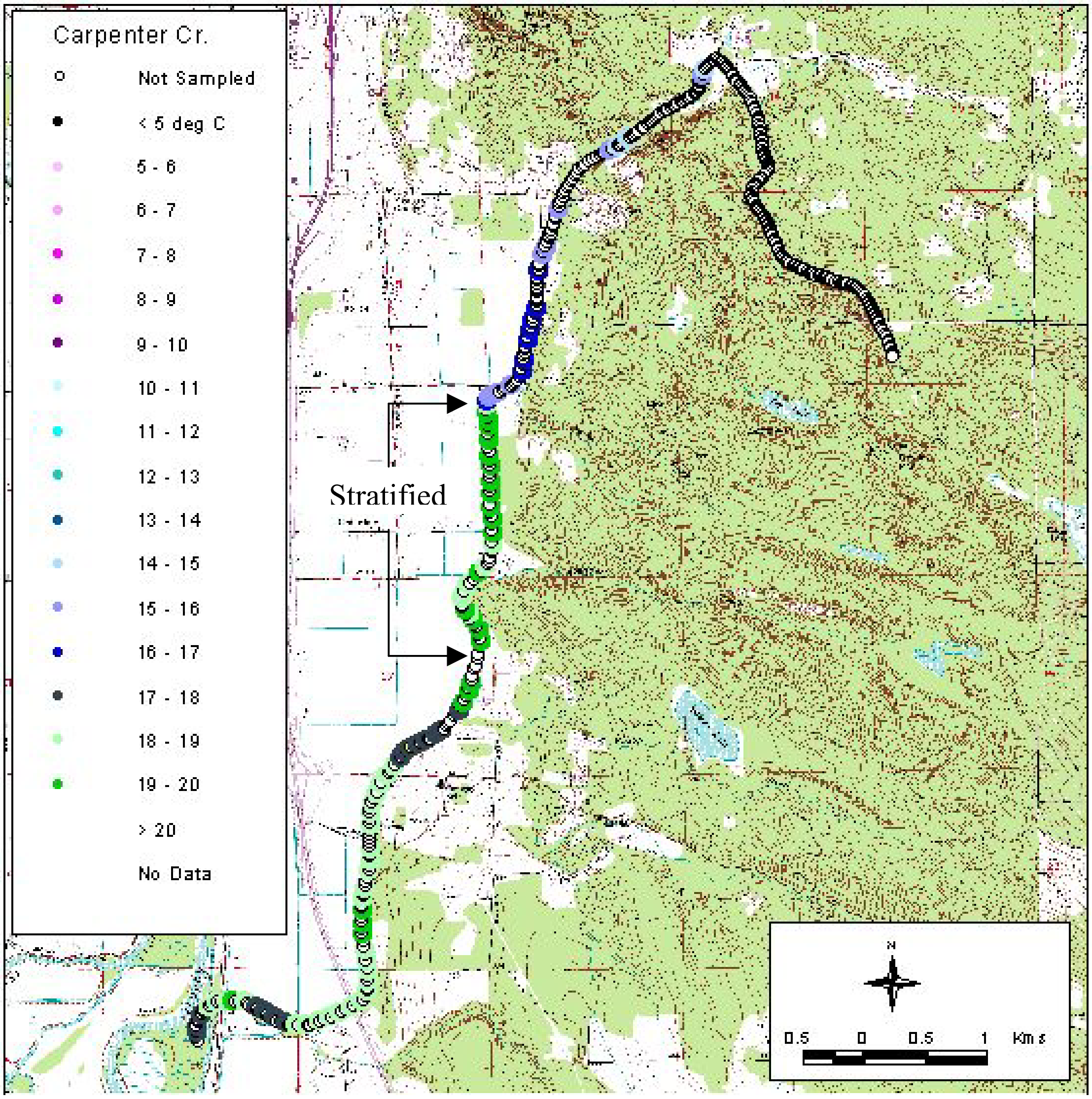


Figure 16 – Point pattern map of the TIR survey of Carpenter Creek, WA. The map shows the canal portion of the stream as well as the headwater areas that could not be sampled.

Nookachamps Creek

Nookachamps Creek was surveyed from the Skagit River upstream to Lake McMurrey, a total of 14 miles. The median temperatures for each sampled image of Nookachamps Creek were plotted versus the corresponding river mile (Figure 17). Surface water inflows (i.e. tributaries, canal returns, etc.) detected in the images are labeled on the profile. The survey included the right bank (*looking downstream*) of Big Lake and lake surface temperatures were sampled during the analysis.

Downstream of Lake McMurrey, Nookachamps Creek was small and difficult to detect through the riparian canopy. Measured stream temperatures between the outlet of Lake McMurrey and the inlet of Big Lake ranged between 14.4°C and 16.4°C. The surface of Big Lake was ≈21.0°C. Nookachamps Creek is a canal downstream of Big Lake and temperatures remained near 20.0°C to river mile 6.7. Stream temperatures decreased by ≈2.0°C between river mile 6.7 and 6.4 near the intersection of two canals. Stream temperatures were consistent (≈18.0°C) between river miles 6.4 and 4.0 before increasing to a local maximum of 20.2°C at river mile 3.1. This temperature increase corresponded to an area labeled as Barney Lake on the topographic maps. The inflow of the East Fork Nookachamps Creek at river mile 2.6 lowered mainstem temperatures by 2.3°C. Water temperatures in Nookachamps Creek were 18.9°C at the confluence of the Skagit River.

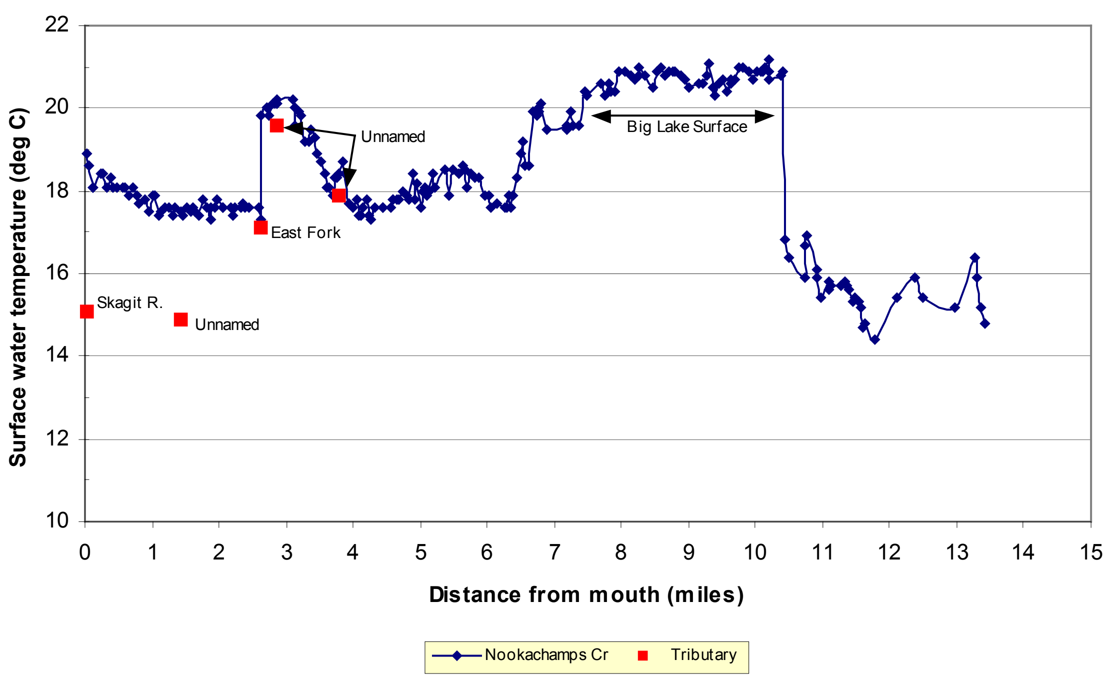


Figure 17 – Median channel temperatures versus river mile for Nookachamps Creek, WA (8/31/01).

Discussion

Aerial surveys were conducted on Carpenter Creek and Nookachamps Creek in the lower Skagit River basin. The surveys were conducted on August 31, 2001 during the mid-afternoon in order to assess low flow high summer temperatures. The flights were postponed by 10 days due to a rainstorm that occurred on August 20th. However, despite recent rains, both streams had areas that showed little detectable surface water. On August 31, clouds increased during the afternoon and were accompanied by generally lower air temperatures. Lowered air temperatures resulted in lower thermal contrast between the water and land surfaces.

Both streams had significant channel alterations through much of their lower reaches. The surface temperature patterns in the canals varied based on inputs from other surface inflows (i.e. tributaries, other canals, etc.), intermittent stratification, and some vegetation at the water surface. On Carpenter Creek, surface water was not detected at several locations along the canal. In the upper reaches of both surveys, the streams were very difficult to detect due to their small size and masking by the riparian vegetation. The imagery collected in the Skagit River basin provides a basis for assessing riparian and channel conditions.

Follow-on

The following is a list of potential uses for these data in follow-on analysis (based on Faux et. al. 2001 and Torgersen et. al. 1999):

1. The patterns provide a spatial context for analysis of seasonal temperature data from in-stream data loggers and for future deployment and distribution of in-stream monitoring stations. How does the temperature profile relate to seasonal temperature extremes? Are local temperature minimums consistent throughout the summer and among years?

2. The database provides a method to develop detailed maps and to combine the information with other spatial data sets. Additional data sets may include factors that influence heating rates such as stream gradient, elevation and aspect, vegetation, and land-use. In viewing the temperature patterns in relation to other spatial factors, correlations are often apparent that provide a more comprehensive understanding of how the stream is thermally structured.

3. What is the temperature pattern within critical reach and sub-reach areas?

4. The TIR and visible band images provided with the database can be aggregated to form image mosaics. These mosaics are powerful tools for planning fieldwork and for presentations.

5. The longitudinal temperature profiles provided in this report provide a spatially extensive, high resolution reference for water temperature status in the basin. Because stream temperature patterns can change as a result of landscape alteration or disturbance, the data provided in this report can be used to assess the impacts of land-use practices and the effects of restoration efforts in the basin.

6. Stream temperature profiles provide a spatially continuous data set for the calibration of reach and basin scale stream temperature models.

7. Color videos as well as digitized visible band images provide a means to evaluate in-stream habitat and riparian/floodplain conditions at the time of the survey.

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Appendix A – Stillaguamish River Basin Images

Appendix B – Skagit River Basin Images